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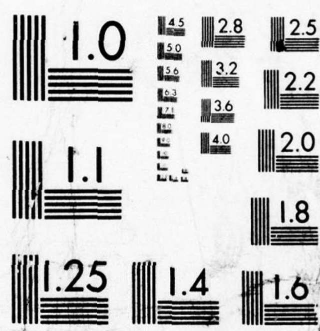

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FOIL BEARING INVESTIGATION

Numerical Solution of the Planar Hydrostatic Foil Bearing

Prepared Under: Contract No. N00014-77-C-0021
Task NR 062-297
Office of Naval Research

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TABLE OF CONTENTS

ABSTRACT

The steady state problem of the planar hydrostatic foil bearing is analyzed and solved numerically. Two techniques of solution are used. One method is simulation in time with asymptotic approach to steady state. This is achieved by a preprocessor which automatically sets up the numerical computer program. The second method is an iterative shooting technique. The results agree well with one another. Curves of pressure and typical film thickness versus flow are presented.

NOMENCLATURE

G	constant found from the solution of Eqn. (25)
h	local film thickness
$\bar{h}$	dimensionless film thickness h/r_o
$\bar{h}_a$	dimensionless distance of foil asymptote to cylinder
H	stretched film thickness coordinate
$\bar{H}, \hat{H}$	auxiliary normalized values of H for computational purposes
m, n	exponents, to be determined
p	local pressure in film
p_a	ambient pressure
Q	volume flow rate per unit bearing width
R	local radius of curvature
r_o	cylinder radius
t	time
T	foil tension per unit width
ϵ	$\frac{12\mu Q}{r_o T}$ dimensionless flow rate
μ	gas viscosity
Π	dimensionless pressure
θ	angular coordinate (origin at point of tangency)
τ	dimensionless time
ξ	stretched angular coordinate
$\bar{\xi}, \hat{\xi}$	auxiliary normalized values of ξ for computational purposes

Subscripts

c	pertains to cylinder center
g	pertains to source location (groove)
t	pertains to point of tangency
∞	pertains to end of lubrication zone

INTRODUCTION

Despite considerable effort in the field of foil bearings over the past two decades, an analysis of hydrostatic foil bearings has not been published. This problem is of interest in magnetic recording and elsewhere. The purpose of this report is to fill this gap.

The initial goal of this investigation was, actually, to illustrate the applicability of a preprocessor computer program for the automatic solution of partial differential equations. Ironically, it turned out, the automatic solution was only partly successful and numerical difficulties were encountered in certain parameter ranges, requiring some human intervention. Consequently, an alternative approach was utilized and a complete set of data curves generated. It is felt, however, that the numerical experience gained in this effort as well as the concepts of the preprocessor are of interest and, therefore, they are reported here as well as the solution of the particular problem at hand.

HYDROSTATIC FOIL BEARING MODEL

Let the configuration shown in Figure 1 be studied. Here, an infinitely wide, hydrostatic, cylindrical, perfectly flexible foil bearing with incompressible lubricant is depicted schematically. In this configuration, one line feed source is located at $\theta = \theta_g$. A second line source is symmetrically situated at the other side of the bearing. It is assumed that the feed pressure p_g is prescribed and maintained constant. The film thickness and pressure are, then, governed by the following differential equations:

$$\frac{\partial}{\partial \theta}\left(h^3 \frac{\partial p}{\partial \theta}\right) = 12 \mu r_o^2 \frac{\partial h}{\partial t} \tag{1}$$

$$p - p_a = \frac{T}{R} = \frac{T}{r_o}\left(1 - \frac{1}{r_o}\frac{\partial^2 h}{\partial \theta^2} + \ldots\right) \tag{2}$$

Using the dimensionless representation

$$\bar{h} = \frac{h}{r_o}$$

$$\Pi = \frac{p - p_a}{T/r_o}$$

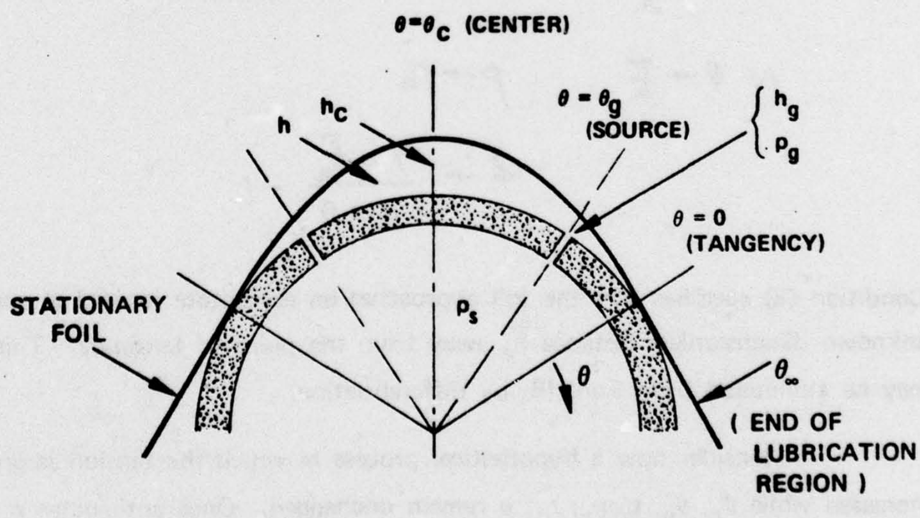

Figure 1 Cylindrical Hydrostatic Foil Bearing

and restricting the problem to steady state, Eqns (1), (2) may be rewritten as

$$\bar{h}^3 \frac{\partial \Pi}{\partial \theta} = -\frac{12\mu Q}{r_o T} \tag{3}$$

$$\Pi = 1 - \frac{\partial^2 \bar{h}}{\partial \theta^2} + \ldots \tag{4}$$

where Q is an integration constant representing the volume flow rate per unit width. Eqns. (3), (4) may be combined to:

$$\bar{h}^3 \frac{\partial^3 \bar{h}}{\partial \theta^3} = \epsilon + \ldots \tag{5}$$

where the dimensionless flow rate ϵ is defined by

$$\epsilon = \frac{12\mu Q}{r_o T}$$

It may be observed that under steady conditions there is no flow in the region $\theta_c \leqslant \theta < \theta_g$ (due to symmetry we restrict our treatment to one half of the problem). The pressure in this region is, therefore, uniformly $p=p_g$. In dimensionless form:

$$\Pi = \Pi_g \equiv \frac{p_g - p_a}{T/r_o}$$

The boundary conditions are:

At $\theta = \theta_g$ $\quad \bar{h}, \bar{h}'$ and Π are continuous (6)

As $\theta \rightarrow \frac{\pi}{2}$ $\quad p \rightarrow p_a$ (7)

$$\bar{h} \rightarrow \frac{1+\bar{h}_a}{\cos\theta} - 1 \tag{8}$$

Condition (8) specifies that the foil approaches an asymptote located at some small unknown dimensionless distance $\bar{h}_a$ away from the point of tangency. This unknown may be eliminated from Eqn. (8) by differentiation.

Consider now a hypothetical process in which the tension is gradually increased while θ_c, θ_g, p_g-p_a, r_o, μ remain unchanged. Once anticipates a corresponding

reduction of flow, or of ϵ. (Note that this process implies either a change in restriction or in the source pressure, to maintain a constant p_g despite changes in Q). Following a derivation analogous to Ref [1] one assumes

$$H = \frac{\bar{h}}{\epsilon^n} \tag{9}$$

$$\xi = \frac{\theta}{\epsilon^m} \tag{10}$$

The following requirements may be imposed: The two sides of Eqn (5) must balance as $\epsilon \rightarrow o$; hence,

$$4n - 3m = 1 \tag{11}$$

Secondly, at least one variable term in Eqn (2) must not vanish as $\epsilon \rightarrow o$; hence,

$$n - 2m = 0 \tag{12}$$

It follows then, that

$$m = 1/5 \tag{13}$$

$$n = 2/5 \tag{14}$$

Thus, in the region $\xi_c \leq \xi < \xi_g$

$$\frac{d^2H}{d\xi^2} = 1 - \Pi_g \tag{15}$$

$$\frac{dH}{d\xi} = (1 - \Pi_g)(\xi - \xi_c) \tag{16}$$

$$H = \frac{1}{2}\left(1 - \Pi_g\right)\left(\xi - \xi_c\right)^2 + H_c \tag{17}$$

where H_c is the unknown dimensionless film thickness at $\xi = \xi_c$

The formulation of the problem in region $\theta_g < \theta$ becomes

$$H^3 \frac{d^3 H}{d\xi^3} = 1 \tag{18}$$

$$\left.\frac{dH}{d\xi}\right|_{\xi=\xi_g} = \left(1 - \Pi_g\right)\left(\xi_g - \xi_c\right) \tag{19}$$

$$\left.\frac{d^2 H}{d\xi^2}\right|_{\xi=\xi_g} = 1 - \Pi_g \tag{20}$$

$$\left.\frac{dH}{d\xi}\right|_{\xi\to\infty} \sim \xi \tag{21}$$

$$\left.\frac{d^2 H}{d\xi^2}\right|_{\xi\to\infty} \sim 1 \tag{22}$$

The fact that we have four boundary conditions for a third order equation indicates that one of the parameters of the problem is not free. The following functional form is, therefore, deduced:

$$\Pi_g = f\left(\frac{\theta_g}{\theta_c}, \xi_c\right) \tag{23}$$

$$H = f\left(\xi; \frac{\theta_g}{\theta_c}, \theta_c\right) \tag{24}$$

The solution techniques are discussed in the Appendix.

RESULTS AND DISCUSSION

The results are summarized in Figures 2-5. They are expressed in terms of two dimensionless parameters, namely: θ_g/θ_c specifying the source location, and $\left(\frac{12\mu Q}{r_o^2 T}\right)^{1/5} / |\theta_o|$ describing flow rate. Figure 2 illustrates some typical tape contours while Figures 3-5 present the dimensionless groove pressure and some characteristic film thicknesses.

The basic behavior of the bearing as it appears from these graphs may be described by means of a conceptual experiment. In this experiment, p_g-p_a is slowly increased while the geometry and tension remain constant. Initially, when the pressure is low, there is no flow (Q=0). When p_g-p_a is increased just above the threshold level of T/r_o, the tape lifts off and starts forming into a "bubble" shape (Figure 2). This contour is typified by a large ratio of h_c/h_t, but the vanishingly small values of both h_c and h_t make the radius of curvature over the source equal to r_o. Increase in pressure above the threshold results in growth of h_c as well as h_t and formation of smaller radius of curvature over the source. The rate of growth of h_c is slower than that of h_t, resulting in a gradual loss of the "bubble" shape. Hence, the radius of curvature over the groove reaches a minimum and then starts growing, eventually exceeding r_o. This growth causes the impedance of the bearing to decrease and the flow to increase. The greater radius of curvature implies, however, that, at the same time, the pressure required to support the foil tension is smaller. The above behavior results in the unexpected phenomenon that the same value of p_g generates two distinct flow rates. This should not be surprising, however, if one remembers that the shape of the flow channel, formed by the foil, is markedly different in the two cases.

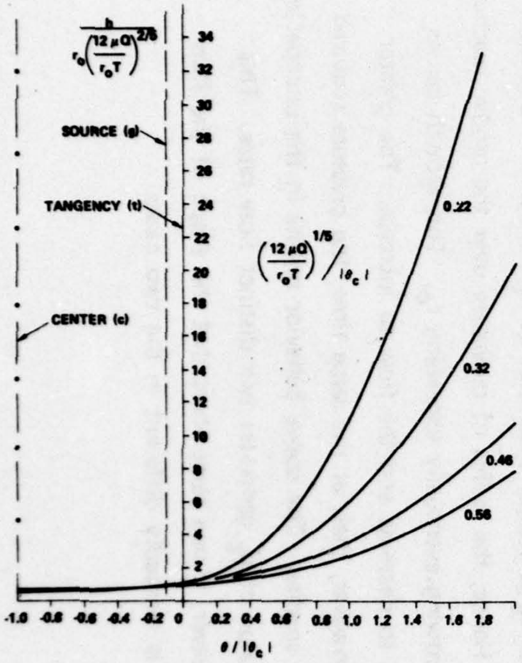

Figure 2a

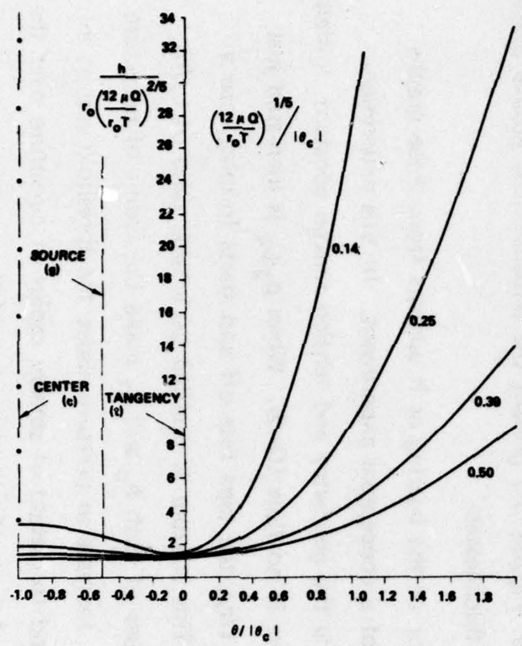

Figure 2b

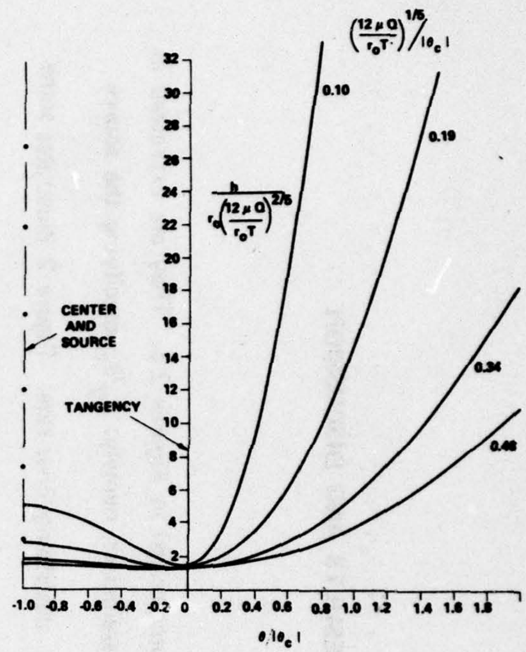

Figure 2c

Figure 2a Tape Contours for a Range of Flow Rates With $\theta_g/\theta_c = 0.1$

Figure 2b Tape Contours for a Range of Flow Rates With $\theta_g/\theta_c = 0.5$

Figure 2c Tape Contours for a Range of Flow Rates With $\theta_g/\theta_c = 1.0$

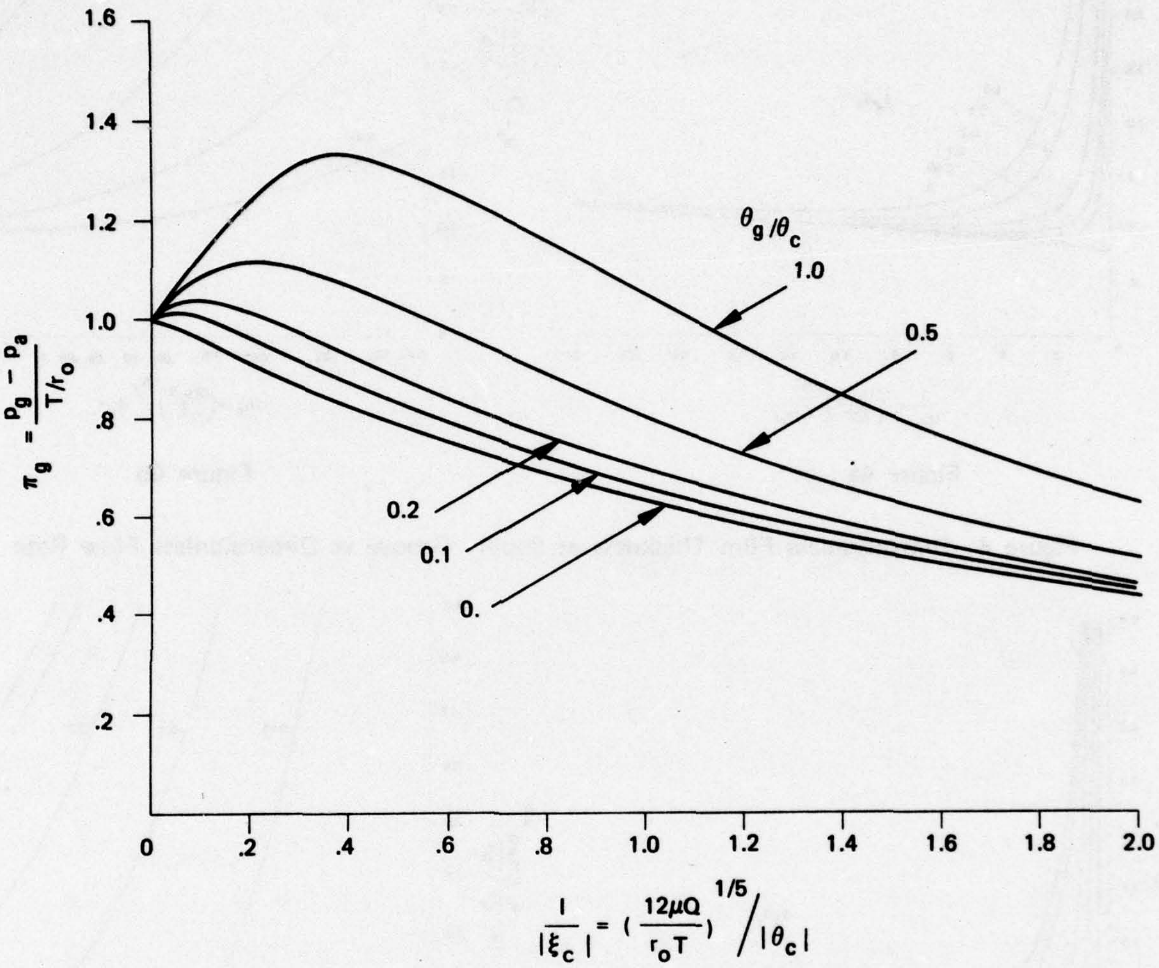

Figure 3 Dimensionless Pressure Drop vs Dimensionless Flow Rate Across Foil Bearing

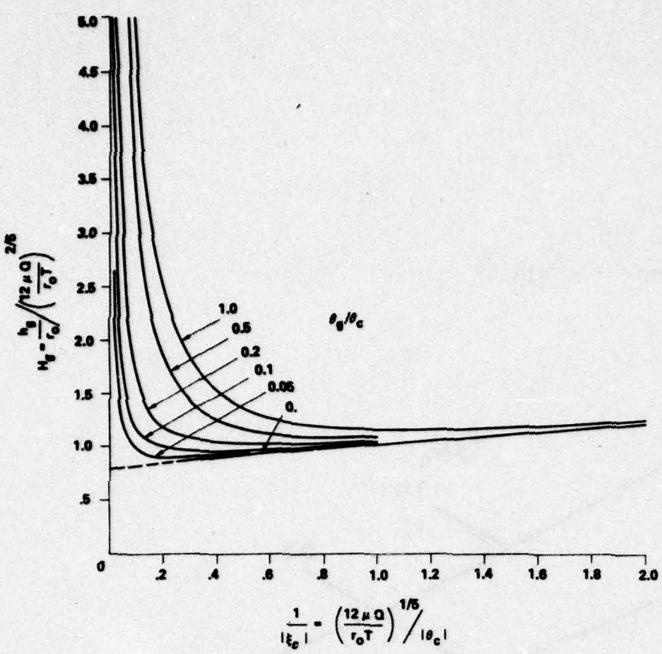

Figure 4a

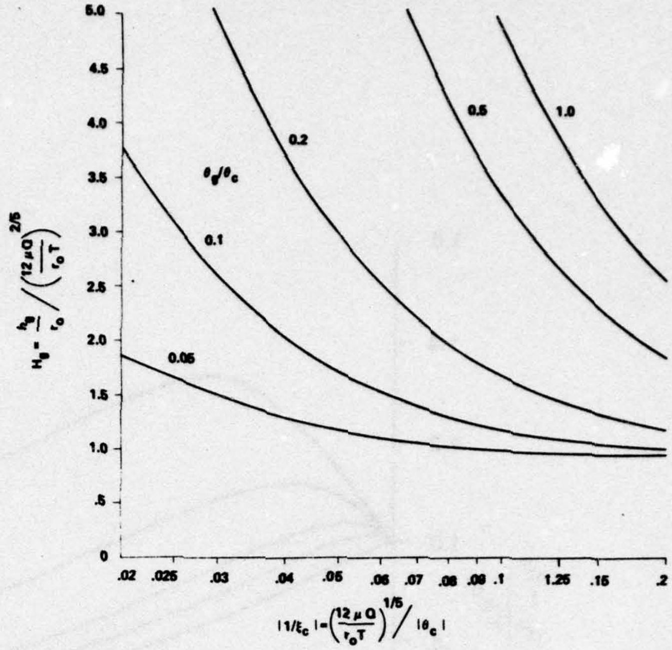

Figure 4b

Figure 4 Dimensionless Film Thickness at Supply Groove vs Dimensionless Flow Rate

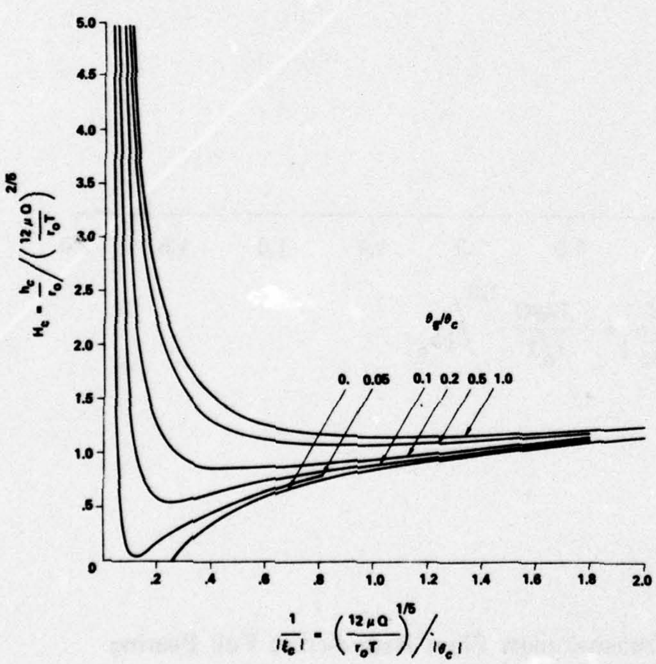

Figure 5a

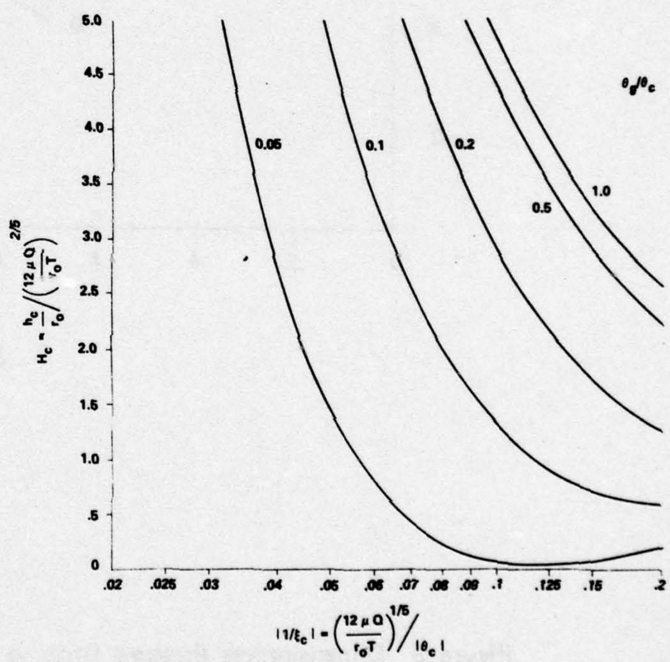

Figure 5b

Figure 5 Dimensionless Film Thickness at Cylinder Center vs Dimensionless Flow

A natural question which arises, is what flow rate will the physical system select in view of the ambiguity. The analysis in this work, determines only the static equilibrium conditions and not their stability and, therefore, cannot provide a complete answer to the question. Nevertheless, a limited insight will be provided in the following discussion.

At the onset let it be noted that the assumption has been implicity made, that p_g may be controlled independently of Q. In any practical situation the restrictor characteristic presents a curve of p_g vs. Q, which may be superimposed on Figure 3. The intersection determines possible operating points which are schematically illustrated in Figure 6.

Neglecting the effect of damping which may be brought out only by a dynamic analysis, it may be shown that intersections of type A, C tend to be stable whereas intersections of type B tend to be unstable. The argument is essentially as follows. Considering point B for example, a downward fluctuation in p_g causes the bearing outflow to exceed the supply through the restrictor. This tends to push the operating point further down from B by causing a deficiency in fluid at the bearing inlet. Thus, for an intersection of restrictor characteristic and film characteristic such as that shown at B, a disturbance in p_g away from the equilibrium point results in a further excursion of the operating point in the same direction. However, for intersections of types A or C, disturbances in p_g from the equilibrium point result in a restorative effect, suggesting stability.

Another observation of interest is that $\theta_g/\theta_c \approx 0.05$ is a threshold value, below which contact between the tape and the cylinder may arise. In these situations the source is located too close to the point of tangency for useful operation. When the flow is minute, a noncontact situation is possible. For slightly higher flow rates, the seal effect at the tangency point disappears and flotation of the foil cannot be maintained throughout the wrap angle.

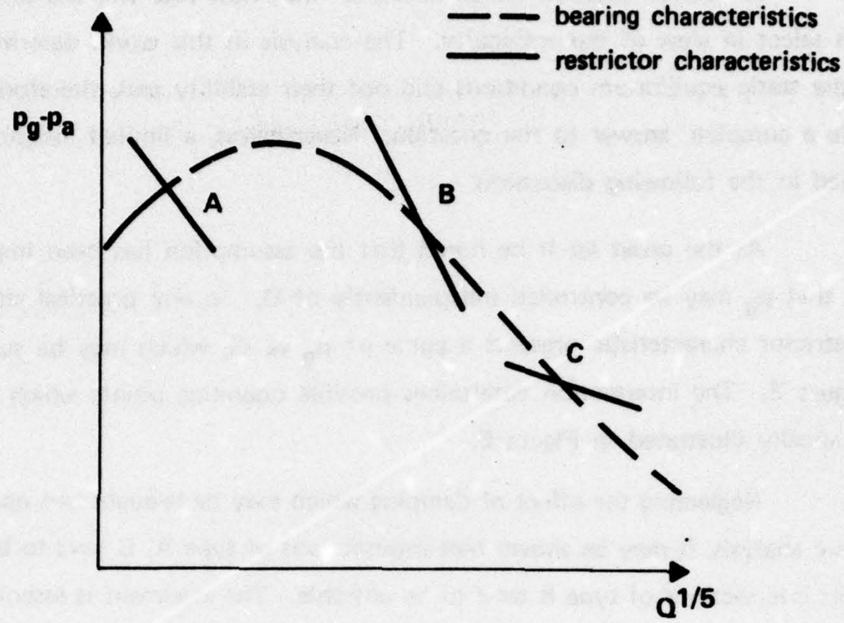

Figure 6 Schematic View of Various Possibilities of Operating Points

APPENDIX I: PREPROCESSOR SOLUTION

PURPOSE OF PREPROCESSOR

With present-day powerful computers, the engineer has at his disposal an invaluable tool for optimization and evaluation of design parameters. Frequently, this evaluation is based on numerical simulation of the behavior of a physical model represented by a partial differential equation (PDE). In order to perform the simulation, it becomes necessary, in such cases, to discretize the partial differential equation (PDE) and to write a computer program that will solve the resulting difference equation and print or display the results numerically and/or graphically. This task is, often, time-consuming and usually requires several debugging runs.

Though laborious, this programming effort, commonly, consists of rather similar subtasks. In general, the programming job may be described as the insertion of problem dependent details into a basic program template designed for the particular algorithm and a broad class of equations. Consequently, it is feasible to carry out this process, too, with the aid of the computer. This is done by means of a preprocessor or a precompiler. The precompiler is a computer program which accepts an input describing the partial differential equation and its boundary conditions in a concise and readable mathematical symbolism, and outputs a high level language (e.g., PLI) program which is then compiled by the language compiler just like a human-written program. The compiler-generated object program is finally executed. (Figure A1).

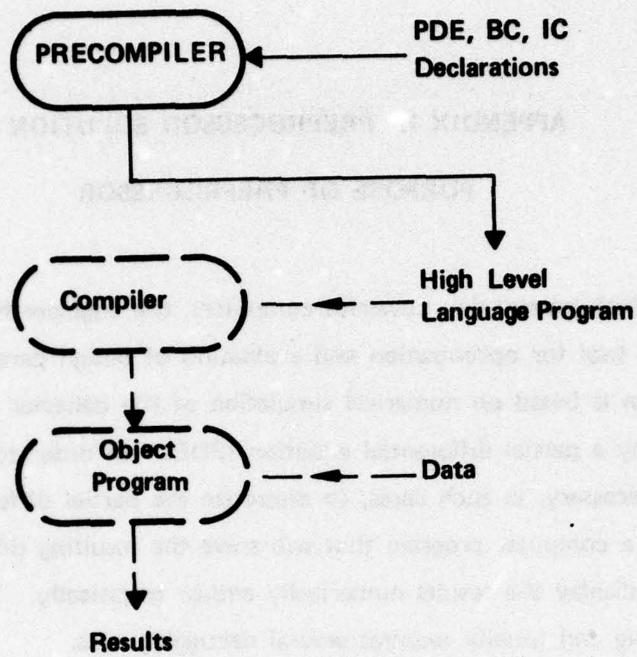

Figure A1 Schematic View of the Role of the Precompiler in Problem Solution. (Broken lines indicate conventional computer solution. Solid lines add the effect of the precompiler.)

In this report, we would limit the discussion to a precompiler for the class of parabolic, high order, one dimensional partial differential equations. We will restrict ourselves, further, to the implicit solution algorithm. This class of problems is still rather broad; and in particular, it is applicable to many foil-bearing problems.

FORMULATION

In order to allow solution by means of a program generated by our precompiler for parabolic partial differential equations, the formulation (18) - (22) for H and Π_g will be replaced by the following alternative formulation defining a function $\bar{H}(\bar{\xi},\tau)$. $\bar{H}$ will later be transformed to the desired function $H(\xi)$.

$$-\frac{\partial^4 \bar{H}}{\partial \bar{\xi}^4} \cdot \bar{H}^3 - \frac{\partial^3 \bar{H}}{\partial \bar{\xi}^3} 3\bar{H}^2 \frac{\partial \bar{H}}{\partial \bar{\xi}} = \frac{\partial \bar{H}}{\partial \tau} \tag{25}$$

$$\bar{H}\Big|_{\bar{\xi}=\bar{\xi}_g} = \bar{H}_g \tag{26}$$

$$\frac{\partial \bar{H}}{\partial \bar{\xi}^2} \cdot (\bar{\xi}_g - \bar{\xi}_c) - \frac{\partial \bar{H}}{\partial \bar{\xi}}\Big|_{\bar{\xi}=\bar{\xi}_g} = 0 \tag{27}$$

$$\frac{\partial \bar{H}}{\partial \bar{\xi}}\Big|_{\bar{\xi}=\bar{\xi}_\infty} \sim \bar{\xi} \tag{28}$$

$$\frac{\partial^2 \bar{H}}{\partial \bar{\xi}^2}\Big|_{\bar{\xi}=\bar{\xi}_\infty} \sim 1 \tag{29}$$

When a steady state solution, $\bar{H}\left(\bar{\xi}; \frac{\bar{\xi}_g}{\bar{\xi}_c}, \bar{\xi}_c, \bar{H}_g\right)$ satisfying these requirements is obtained, a parameter G, elaborated upon later, may be evaluated from

$$G = \bar{H}^3 \frac{\partial^3 \bar{H}}{\partial \bar{\xi}^3} \tag{30}$$

$H(\xi), H_c, \xi_c$ and π_g may then be obtained from the numerical solution obtained by the transformations

$$H = \bar{H}/G^{4/5} \tag{31}$$

$$\xi = \bar{\xi}/G^{1/5} \tag{32}$$

$$\pi_g = 1 - \left.\frac{\partial^2 \bar{H}}{\partial \bar{\xi}^2}\right|_{\bar{\xi}=\bar{\xi}_g} \tag{33}$$

$$H_c = \bar{H}_g - \tfrac{1}{2}(1-\pi_g)(\xi_g - \xi_c)^2 \tag{34}$$

Substitution of the transformations (31) - (34) into Eqns (25) - (29) will verify that the function H indeed satisfies all the requirements (18) - (22). The equality of the ratios $\bar{\xi}_g/\bar{\xi}_c$, ξ_g/ξ_c, θ_g/θ_c simplifies the presentation of the results.

The value of G, though theoretically a constant, may be expected to vary somewhat with ξ due to truncation and round-off errors in the solution. It was rather unexpected, however, to find that in certain parameter ranges unacceptable nonuniformities in G were found numerically. However, for those parameter values for which the values of G were sufficiently uniform, the results agreed very well with those of the alternative technique described below.

PRECOMPILER INPUT

The precompiler input corresponding to Eqns. (25) - (29) is shown in Figure A2. The first line identifies the user supplied program name EXTP. This name is used as a prefix in naming subroutines generated by the preprocessor to facilitate readability of the generated program by the user. Next, room is provided for some options. In the present precompiler version, this is superfluous since only one option now exists. Next, one may note in Figure A2 some text enclosed between /* . . . */. This text constitutes a comment which is ignored by the precompiler. Following this text, some declarations appear. These declarations categorize identifiers as parameters, independent, dependent and entry names. Parameters signify variables whose numerical value will be read in at run time by a standard read statement. Entry *names, not illustrated in Figure A2, are* names of library or user defined subroutines, and so on.

Following the preamble, the actual statements of the differential *equation* (DE), *boundary conditions* (BC), and initial conditions (IC) are provided. The specification: BC LOW (XIR * XIC, *) means: This is a boundary condition at the low end of the interval of independent variable #1; i.e., X whose value at that point is the expression XIR * XIC†. In addition, the BC is valid for any value (*) of independent variable #2, i.e., T. The rest of the input is self-explanatory.

†Naturally, this value could have been a constant or a variable name.

```
EXTP:   PROCEDURE OPTIONS(PARABOLIC);
        /* EXTERNALLY PRESSURIZED FOIL BEARING ANALYSIS.
         STATIONARY, INCOMPRESSIBLE, PLANAR, PERFECTLY
         FLEXIBLE, REFERENCED TO A CYLINDRICAL SURFACE.
         TWO SOURCES, SYMMETRICALLY LOCATED ABOUT CENTER. */

                DECLARE
         XIC    PARAMETER,  /* COORDINATE OF CENTER */
         XIR    PARAMETER,  /* XIG/XIC , WHERE XIG=COORDINATE OF SOURCE */
         XI8    PARAMETER,  /* COORDINATE, END OF LUBRICATION ZONE */
         HG     PARAMETER,  /* H VALUE AT SOURCE */
         HMIN   PARAMETER;  /* INITIAL VALUE OF H AT TANGENCY POINT */
                DECLARE
         X     INDEPENDENT(1),   /* 1ST VARIABLE IN LIST, SPATIAL COORDINATE */
         T     INDEPENDENT(2),  /* 2ND VARIABLE IN LIST, TIME COORDINATE */
         H     DEPENDENT; /* DIMENSIONLESS FILM THIKNESS, H_BAR IN PAPER */

DE:                     @4X(H)*(-H**3) +@3X(H)*(-3.*H**2*@X(H))=@T(H);
BC LOW (XIR*XIC,*):     H=HG;
BC LOW (XIR*XIC,*):     @2X(H)*(XIR-1.)*XIC+@X(H)*(-1.)=0.;
BC HIGH (XI8,*):        @X(H)=XI8;
BC HIGH (XI8,*):        @2X(H)=1.;
IC:                     H=HMIN+X**2/2.;
        END;
```

Figure A2 Precompiler Input (Corresponding to Eqns (25)-(29))

PRECOMPILER STRUCTURE

The precompiler is composed of three sub-programs: 1. Lexical, analyzer, 2. Syntactic and semantic analyzer; and 3. Synthesizer.

The lexical analyzer consists of a small driver section which picks an input character, decodes it, and branches to several possible routines accordingly. These routines identify literals (e.g., 2.0, 20.E-1, 2), identifiers (e.g., XIR, SQRT), reserved words (e.g., DE, BC), comments, etc. Identifiers and literals are stored in a table. The output of the lexical analyzer is a uniform stream of pairs of descriptors, the first of which indicates the type of element encountered (e.g., **, +, identifier). The second descriptor points, when necessary, to a table of additional information (e.g., the actual identifier's name).

The syntactic/semantic analyzer scans the pairs emitted by the lexical analyzer and parses them. Parsing means, in principle, matching of a precompiler input statement to a set of prototype statements describing the grammar of the input language. For example, the two prototype statements

assignment ⇐ variable = expression
expression ⇐ term [+ term]

where the brackets indicate zero or more repetitions of elements of the enclosed form, may be matched to a fortran statement such as

A = B + C

Several parsing methods are available in compiler design. Parsing was done in this work by recursive descent [2]. In essence, for each of the grammar nonterminal symbols (e.g., assignment, variable, term),there is a logical recursive subroutine which returns "true" or "false" depending on whether the terminal language symbol

(e.g., A, B, =, +) can be matched to the prototype. A subroutine called "assignment" calls the subroutine "variable"; and if it is true that the symbol is a variable, checks whether the next symbol in the input string is a "=", and so on. This parsing process is continued until the input structure is matched to the syntax rules or else there is no match due to a user grammar error. Once a match is achieved, reference is made to a set of routines which produce the desired output segment for the final high-level language program. For example, since the differential equation is converted into a set of algebraic equations in matrix form, the routines will generate assignment statements for the coefficients.

The synthesis phase collects the segments generated by the syntactic/semantic phase and inserts them into a prearranged program template. The template consists of a high-level language (PLI) program for solution of the desired class of equations by an implicit algorithm. The template consists, basically, of the following slots:

Main program -- a driver routine containing a slot for user input.

Matrix generator -- sets up the coefficient matrix for PDE solution and for BC.

Initializer -- the particlar initial conditions are set up.

Output -- fixed format output of PDE solution is set up with some user control over the amount of printout).

The generated program uses a diagonal band matrix solver which is a fixed subroutine. This routine takes as its input the matrix equation and its bandwidth and provides the solution.

With standard catalogued procedures (such as we have developed for OS 360), the operation of the program is quite simple. The input has to be stored in a data set. Data sets may optionally be provided by the user for storing the generated PLI program*, the object program, and the output. The precompiler is written in PLI and is, thus, machine independent for all machines for which PLI compiler is available.

*A listing of the generated computer program is given in Appendix III.

APPENDIX II: O.D.E. SOLUTION

Let Eqns (18) - (22) be reformulated in terms of alternative variables $\hat{H}$ $(\hat{\xi})$, in order to permit solution as an ordinary DE. Later the solution for $\hat{H}$ will be transformed back into H (ξ). The reformulated problem is:

$$\hat{H}^3 \frac{d^3\hat{H}}{d\hat{\xi}^3} = 1 \tag{35}$$

At $\hat{\xi} = 0$

$$\hat{H} = \hat{H}_g \tag{36}$$

$$\hat{H}' = \hat{H}'_g \tag{37}$$

$$\hat{H}'' = \hat{H}''_g \tag{38}$$

Integration as an initial value problem is terminated when $\hat{H}''$ tends to approach a constant say $\hat{H}''_\infty$. The exact termination value is not critical, but it should be sufficiently large so that $\hat{H}_\infty/\hat{H}_g >> 1$. It may be verified that the conversion

$$H = \hat{H}\cdot\left(\hat{H}''_\infty\right)^{3/5}$$

$$\xi = \left(\hat{\xi} - \hat{\xi}_\infty - \frac{\hat{H}'_\infty}{\hat{H}''_\infty}\right)\cdot\left(\hat{H}''_\infty\right)^{4/5}$$

transforms the solution aposteriori to that of the original coordinates. The parameters of the problem which has been solved are found by:

$$\pi_g = 1 - \hat{H}''_g / \hat{H}''_\infty$$

$$\xi_g = \hat{H}'_\infty / \hat{H}''^{1/5}_\infty - \hat{\xi}_\infty \hat{H}''^{4/5}_\infty$$

$$\xi_c = \hat{H}'_\infty / H''^{1/5}_\infty - \hat{H}''^{4/5}_\infty \left(\hat{H}'_g / \hat{H}''_g + \hat{\xi}_\infty \right)$$

$$H_c = H_g - \frac{1}{2} \left(1 - \pi_g \right) \left(\xi_g - \xi_c \right)^2 .$$

APPENDIX III: LISTING OF COMPUTER PROGRAM GENERATED BY PRECOMPILER

```
EXTP:   PROCEDURE OPTIONS (MAIN);
                                          DECLARE
        DI$ BINARY FIXED(15,0)INITIAL (1),/*PRINT INCR*/
        DX1$  DEC FLOAT(6) INITIAL(0.1),/*SPATIAL STEP*/
        DT1$  DEC FLOAT(6) INITIAL(0.1),/*TIME STEP */
        IK$  BINARY FIXED(15,0) INITIAL(1) ,/*PRINT FREQUENCY */
        IL$    BIN FIXED(15,0) INITIAL(1),/*SPATIAL COUNTR LO*/
        IH$  BIN FIXED(15,0)INITIAL(11),/*SPATIAL COUNTER HI*/
        JFIN   BINARY FIXED (15,0) INITIAL (1),/*NO OF STEPS*/
        JS$   (KLIN$) BINARY FIXED (15,0), /*LINE NUMBER */
        KBC$   BINARY FIXED (15,0) INITIAL ( 2),/*HALF BAND OF MATRIX */
        KBCP1$ BINARY FIXED (15,0) INITIAL ( 3),
        KLIN$   BINARY FIXED (15,0) INITIAL (9), /*LINES STORED*/
        ORDER$   BINARY FIXED (15,0) INITIAL ( 4);
   L1:  GET DATA (
        XIC,HG,XIR,HMIN,XI8,
        JFIN,IL$,IH$,DI$,DT1$);
        CALL HD_EXTP;
        GO TO L1;

HD_EXTP: PROCEDURE;
                                          DECLARE
        A$    (IL$-ORDER$/2:IH$+ORDER$/2,-ORDER$/2:ORDER$/2+1)
          DEC FLOAT(16),/*MATRIX EQN*/
        EMATRXP    ENTRY, /*SOLVE MATRIX EQN */
        ESTOREP    ENTRY,/*STORE FOR PRINTING*/
        EWRITEP    ENTRY ,/* PRINT ROUTINE */
        H       (1:KLIN$,IL$:IH$) DEC FLOAT(16);/*DEPENDENT VAR*/
        A$=0.;
        XL$=XIR*XIC;
        XH$=XI8;
        DX1$=(XH$-XL$)/(IH$-IL$);
        PUT DATA (
        XIC,HG,XIR,HMIN,XI8,
        JFIN,IL$,IH$,DI$,DT1$);
        PUT DATA (DX1$);
        ILP$=IL$+KBC$;
        IHM$=IH$-KBC$;
        DX2$=DX1$*DX1$;DX3$=DX2$*DX1$;DX4$=DX3$*DX1$;
        CALL IC_EXTP;
```

```
L2:   DO JR$=1 TO JFIN    ;
      CALL EQ_EXTP;
      CALL BC_EXTP;
      CALL EMATRXP ;
      IF (MOD(JR$,IK$)=0) THEN CALL ESTOREP;
      IF((K$=KLIN$) | (JR$=JFIN)) THEN CALL EWRITEP;
      END L2;
      RETURN;

IC_EXTP: PROCEDURE;
      JR$=0;
      K$=1;
      JS$(K$)=JR$;
      DO I$=IL$ TO IH$;
         H(K$,I$)=HMIN+(I$-IL$)*DX1$**2/2.;
         END;
      RETURN;
      END IC_EXTP;

EQ_EXTP: PROCEDURE;
      DO I$=ILP$ TO IHM$    ;
      C4$=(-H(K$,I$)**3);
      C3$=(-3.*H(K$,I$)**2*(+1./DX1$*H(K$,I$+0)
      ));
      A$(I$,-2)=(+1./DX4$*C4$-.5/DX3$*C3$)*DT1$;
      A$(I$,-1)=(-4./DX4$*C4$+1./DX3$*C3$)*DT1$;
      A$(I$,+0)=(+6./DX4$*C4$+0.*C3$)*DT1$-1.;
      A$(I$,+1)=(-4./DX4$*C4$-1./DX3$*C3$)*DT1$;
      A$(I$,+2)=(+1./DX4$*C4$+.5/DX3$*C3$)*DT1$;
      A$(I$,+3)=-H(K$,I$);
         END;
      RETURN;
      END EQ_EXTP;

BC_EXTP: PROCEDURE;
      A$(IL$,+0)=+1.;
      A$(IL$,+1)=+0.;
      A$(IL$,+2)=0.;
      A$(IL$,KBCP1$)=HG;
      C2$=(XIR-1.)*XIC;
      C1$=(-1.);
      A$(IL$+1,-1)=+2./DX2$*C2$-1.5/DX1$*C1$;
      A$(IL$+1,+0)=-5./DX2$*C2$+2./DX1$*C1$;
      A$(IL$+1,+1)=+4./DX2$*C2$-0.5/DX1$*C1$;
      A$(IL$+1,+2)=-1./DX2$*C2$;
      A$(IL$+1,KBCP1$)=0.;
      A$(IH$,-2)=+0.5/DX1$;
      A$(IH$,-1)=-2./DX1$;
      A$(IH$,+0)=+1.5/DX1$;
      A$(IH$,KBCP1$)=XI8;
      A$(IH$-1,-2)=-1./DX2$;
      A$(IH$-1,-1)=+4./DX2$;
      A$(IH$-1,+0)=-5./DX2$;
      A$(IH$-1,+1)=+2./DX2$;
      A$(IH$-1,KBCP1$)=1.;
      RETURN;
      END BC_EXTP;
```

```
EMATRXP:  PROCEDURE;
                         DECLARE
        (I$,KH$,KV$)  BINARY FIXED (15,0); /*LOOP INDICES */
    PS1: DO I$=IL$ TO IH$;
           DO KH$=1 TO KBCP1$;
              A$(I$,KH$)= A$(I$,KH$)/A$(I$,0);
              DO KV$=1 TO KBC$;
                 IF (KH$=KBCP1$)
                 THEN A$(I$+KV$,KBCP1$)=A$(I$+KV$,KBCP1$)
                    -A$(I$,KBCP1$)*A$(I$+KV$,-KV$);
                 ELSE A$(I$+KV$,KH$-KV$)=A$(I$+KV$,KH$-KV$)
                    -A$(I$,KH$)*A$(I$+KV$,-KV$);
                 END;
              END;
           END PS1;
   PS2:  DO I$=IH$ TO IL$+1 BY -1;
           DO KV$=1 TO KBC$;
              A$(I$-KV$,KBCP1$)=A$(I$-KV$,KBCP1$)
                 -A$(I$,KBCP1$)*A$(I$-KV$,KV$);
              END;
           END PS2;
        RETURN;
        END EMATRXP;

ESTOREP:  PROCEDURE;
                             DECLARE
        IC      BINARY FIXED (15,0)  ;
        K$=1+ MOD(K$,KLIN$);
        JS$(K$)=JR$;
        DO I$=IL$ TO IH$;
           H(K$,I$)= A$(I$,KBCP1$);
           END;
        RETURN;
        END ESTOREP;

EWRITEP:   PROCEDURE;
                             DECLARE
        (IC,KC)        BINARY FIXED  (15,0);
        PUT  EDIT ('I$/JS$',(JS$(IC) DO IC=1 TO K$))
                  (COL(1),A(6),(K$) F(12,0), SKIP(2));
        DO  IC=IL$ TO IH$ BY DI$;
           PUT EDIT (IC,(H(KC,IC) DO KC=1 TO K$))
              (COL (1),F(6,0), (K$) E(12,4));
           END;
        PUT PAGE;
        RETURN;
        END EWRITEP;

        END HD_EXTP;
        END EXTP;
```

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